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Assessing the effects of adaptation measures on optimal water resources allocation under varied water availability conditions

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ABSTRACT

Human activities and climate change have altered the spatial and temporal distribution of water availability which is a principal prerequisite for allocation of different water resources. In order to quantify the impacts of climate change and human activities on water availability and optimal allocation of water resources, hydrological models and optimal water resource allocation models should be integrated. Given that increasing human water demand and varying water availability conditions necessitate adaptation measures, we propose a framework to assess the effects of these measures on optimal allocation of water resources. The proposed model and framework were applied to a case study of the middle and lower reaches of the Hanjiang River Basin in China. Two representative concentration pathway (RCP) scenarios (RCP2.6 and RCP4.5) were employed to project future climate, and the Variable Infiltration Capacity (VIC) hydrological model was used to simulate the variability of flows under historical (1956–2011) and future (2012–2099) conditions. The water availability determined by simulating flow with the VIC hydrological model was used to establish the optimal water resources allocation model. The allocation results were derived under an extremely dry year (with an annual average water flow frequency of 95%), a very dry year (with an annual average water flow frequency of 90%), a dry year (with an annual average water flow frequency of 75%), and a normal year (with an annual average water flow frequency of 50%) during historical and future periods. The results show that the total available water resources in the study area and the inflow of the Danjiangkou Reservoir will increase in the future. However, the uneven distribution of water availability will cause water shortage problems, especially in the boundary areas. The effects of adaptation measures, including water saving, and dynamic control of flood limiting water levels (FLWLs) for reservoir operation, were assessed and implemented to alleviate water shortages. The negative impacts from the South-to-North Water Transfer Project (Middle Route) in the mid-lower reaches of the Hanjiang River Basin can be avoided through the dynamic control of FLWLs in Danjiangkou Reservoir, under the historical and future RCP2.6 and RCP4.5 scenarios. However, the effects of adaptation measures are limited due to their own constraints, such as the characteristics of the reservoirs influencing the FLWLs. The utilization of storm water appears necessary to meet future water demand. Overall, the results indicate that the framework for assessing the effects of adaptation measures on water resources allocation might aid water resources management, not only in the study area but also in other places where water availability conditions vary due to climate change and human activities.

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1. Introduction

Water availability is a principal prerequisite for allocation of water resources. Due to human activities and climate change, the spatial and temporal distribution of water availability has been altered, bringing about daunting challenges in water resources allocation (Arnell et al., 2001; Labat et al., 2004; Immerzeel, 2008; Wang et al., 2016a; Zessner et al., 2017). Notably, water transfer projects directly decrease the amount of water availability in donor areas and increase it in the receiving areas. It is critical to understand how human activities and climate change influence water availability, in order to determine water resources allocation and to ensure adequate access to these resources for users (Schuol

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et al., 2008; Richey et al., 2015). In recent years, numerous studies have assessed the impacts caused by climate change or human activities on hydrological processes and water resources at various scales, such as the basin (Chang et al., 2015; Kundu et al., 2017), national (Liu et al., 2017), regional (Suppan et al., 2008; Kusangaya et al., 2014), and even global (Arnell, 1999; Arnell et al., 2001) scales. The majority of these studies focus on changes in water availability, including the quantification of contribution by climate or land use/cover changes (Herrera-Pantoja and Hiscock, 2015; Kirby et al., 2016; Nepal, 2016), while very few have concentrated on the impacts of the varied water availability on water resources allocation. However, it is important to note that the relationship between optimal water resources allocation and water availability is nonlinear (e.g. the nonlinear reservoir operation rule in optimal water resources allocation applies here). This is because optimal water resources allocation refers to project (e.g. reservoir) operations and it can also alter the spatial and temporal distribution of water supply according to water demand. Therefore, it is unreasonable to equate the impacts of climate change and human activities on water availability to optimal water resources allocation alone. In other words, a gap exists between research on variable water availability and water resources allocation. Hence, it is necessary to integrate hydrological models and water resources allocation models to quantify the nonlinear relationship between the two.

In order to alleviate the impacts of human activities and climate change on optimal water resources allocation, corresponding adaptation measures have been widely adopted to reduce the conflict between supply and demand in water management (Adger et al., 2005; Parry et al., 2007; Hallegatte, 2009; Sun et al., 2015). These topics have been discussed in multiple National Academies of Science reports (PAMRS, 2004; Walkerden, 2006). Water management adaptation options for meeting water demand are categorized into "supply-side" options, which focus on augmenting water availability, and "demand-side" options, which aim to reduce water demand mainly through the efficient use of water (Borgomeo et al., 2014). "Supply-side" management can include reservoir operation (McFarlane et al., 2012), which integrates flood management and water supply. As technological changes will shape some choices for water demand adaptation (Iglesias et al., 2011), water saving measures will be implemented across a wide range of feasible future states (Cosgrove and Loucks, 2015). Therefore, a forward-looking quantitative assessment of adaptation measures on optimal water resources allocation is required for effective adaptation planning and water project operation under a changing environment.

While the approaches developed for optimal water resources allocation based on historical water availabilities are widely accepted for long-term planning purposes (Liu et al., 2010; Szemis et al., 2013; Liu et al., 2014), they are unsuitable for a changing future environment. Taking account of varying water availability in the future, an integrated water resources allocation model is proposed to quantify the nonlinear impacts of water availability on water resources allocation, and to develop a framework for assessing the effects of adaptation measures on water resources allocation.

2. Methodology

2.1. Framework for assessing the effects of adaptation measures on optimal water resources allocation under varied water availability conditions

The framework for assessing the effects of adaptation measures on optimal water resources allocation under varied water availability conditions broadly consists of three parts: (1) the determination of the varied water availability conditions; (2) description of the adaptation measures and (3) optimal water resources allocation.

In order to determine available water resources taking into account climate change and land use/cover changes, hydrological models with forcing typical in Global Climate Model (GCM) outputs have been widely used (Shamir et al., 2015). This allows researchers to quantify the nonlinear impacts of water availability on water resources allocation. Hydrological models and optimal water resources allocation models must be integrated through water availability. If adaptation measures are implemented in the optimal allocation model in the form of constraints (e.g. the rules of reservoir operation from the "supply-side") or inputs (e.g. water saving from the "demand-side"), the effects of the adaptation measures can be assessed by comparing the allocation results. The workflow for this process is shown in Fig. 1.

2.2. Hydrological model for available water resources

The Variable Infiltration Capacity (VIC) hydrological model is adopted to determine the amount of available water resources under a changing climate. It is a physically based and semi-distributed model (Liang et al., 1994; Cherkauer et al., 2003), which was originally developed as a land surface scheme to provide the boundary conditions for GCMs at the University of Washington and Princeton University. It solves water and energy balance equations between land and atmosphere. Thus, it can be used to simulate hydrological processes, including surface flow, base flow, evapotranspiration, snowmelt and the distribution of soil moisture in the uppermost two to three soil layers (Liang et al., 1994, 1996; Cherkauer and Lettenmaier, 1999; Ma et al., 2016). Input data to the VIC hydrological model are grid-based variables that include precipitation, air temperature, downward shortwave (solar) and long-wave radiation, humidity, and land surface characteristics such as the elevation, the land cover type, and the soil characteristics. The sub-grid parameterization of the model, based on

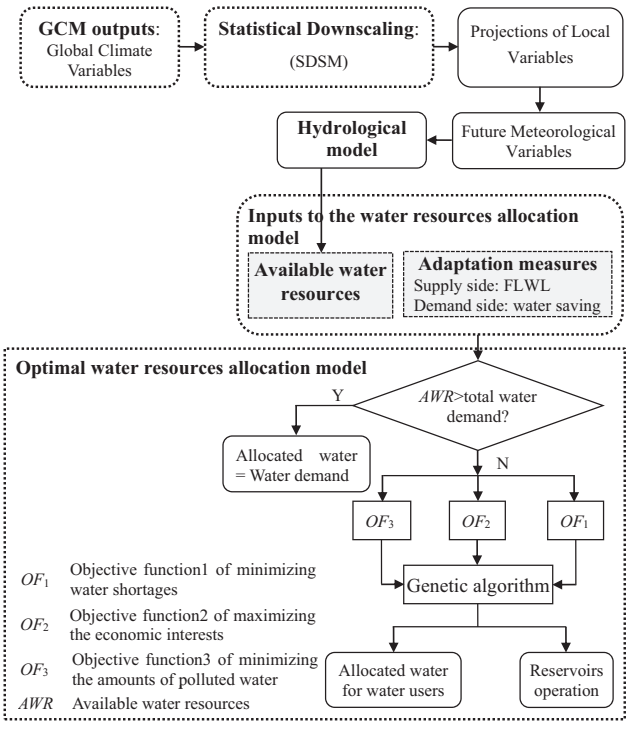

Fig. 1. The workflow used to assess effects of adaptation measures on the optimal water resources allocation under varied water availability conditions.

topography, soil, vegetation, and meteorological data make it distinct from other hydrological models. With these characteristics, the model is designed to consider the heterogeneity of land surface properties and can describe the physical hydrological processes within a model grid cell (Wu et al., 2011). The VIC hydrological model is forced with observed surface meteorological data and outputs (stream discharge, including base flow and direct runoff). It has now been widely used as a hydrological model to assess hydrologic response to climate change (Guo, 2009; Bae et al., 2015; Michelle et al., 2015; Gould et al., 2016; Wang et al., 2016b).

The amount of available water resources in a region can vary widely due to changes in climate. The GCM is the most important tool for studying climate change (Johnson and Sharma, 2009; Chen et al., 2013; Pervez et al., 2014). GCM outputs are metrological variables and will be used as the inputs for hydrological models to reflect hydrologic responses to the climate change. However, the major challenge of linking GCMs to hydrologic models is the vast scale gap between the outputs of climate processes and the requirement of hydrological processes (Bell et al., 2014). The vast scale gap requirements have led to the development of downscaling methodologies. Statistical downscaling models (SDSM) are regression-based and are constructed by deriving empirical relationships between the large-scale GCM predictors and the station-scale predictands. The SDSM can also provide a reliable and less computationally intensive alternative to models using local surface weather variables, and many recent studies have adopted the statistical downscaling methods in the assessment of future climate impact on hydrologic regimes and water resources (Subhrendu and Pruitt, 2011; Meenu et al., 2013; Pervez and Henebry, 2014; Wilby et al., 2014; Singh et al. 2015; Mullan et al., 2016; Tang et al., 2016). The climate variables from the projections of the statistical downscaling model (version 4.2) (Wilby and Wigley, 1997; Haylock et al., 2006), which is a freely available tool that produces high resolution climate change scenarios (Meenu et al., 2013; Wilby and Dawason, 2013), will be used in a hydrologic model to predict the available water resources in the future.

2.3. Optimal water resources allocation model

The optimal water resources allocation model is composed of three components: objective functions, system constraints, and optimization techniques.

2.3.1. Objective functions

As shown in Fig. 1, the objective functions OF_1, OF_2, and OF_3 are described as follows:

(i) Minimisation of water shortages (OF_1).

This objective represents the equal sharing of water resources in each operational zone (an operational zone is a sub-basin determined by the distribution of administrative counties or cities and rivers). This equal sharing of water resources is expressed by the amount of water shortage per capita in every operational zone and is defined as:

$$Minimize\ OF_1(X) = \sum_{t=1}^{12}\left\{\frac{1}{n}\sum\nolimits_{i=1}^{n}\left[\frac{\sum_{j=1}^{l}(DW_{ij}^{t} - x_{ij}^{t})}{NPO_i}\right]\right\}, \quad (1)$$

where t is the number of months (1–12); l is the number of sectors or water users (such as agriculture, industry and domesticity) in every operational zone; n is the number of operational zones; x_{ij}^{t} is the decision variable that represents the water resources allocated to sector j in the ith operational zone in the tth month; NPO_i is the population in the ith operational zone from the statistical yearbook or the results of economic and social development prediction in the future; DW_{ij}^{t} is the water demand of sector j in the ith operational zone in the tth month and can be determined by the quota method. The volume of water demanded in agriculture is calculated by multiplying the estimated area (in hectares) of every measured crop by the net water requirement ($m^3\ ha^{-1}$) of the crop. The volume of industry water demand is determined by the product of Gross Domestic Product (GDP) of industry in the future and the water use per ten thousand Yuan of GDP ($m^3\ Yuan^{-1}\ 10^{-4}$). The volume of domestic water demand is obtained from the product of the number of people and per capita water use (Liu et al., 2010).

(ii) Maximisation of the economic interest (OF_2).

In order to maximize the economic interest of the whole area, the second objective function (OF_2) is defined as the total economic value of the whole basin in a year, that is,

$$Maximize\ OF_2(X) = \sum_{t=1}^{12}\sum_{i=1}^{n}\sum_{j=1}^{l}(x_{ij}^{t} * NER_{ij}), \quad (2)$$

where NER_{ij} is the net economic return per unit of water quantity from sector j in the ith operational zone (RMBYuan /m^3 in our case study). The NERs from agricultural and industrial sectors are calculated as the difference between the total benefit and the total cost of production. The benefit from water use in the domesticity sector cannot be quantified. Since the domesticity sector is the most important sector, its NER is considered simply as the maximum NER values from agriculture and industry.

(iii) Minimization of the amount of waste water (OF_3).

In order to minimize the total amount of waste water in the whole area, the objective function is given as

$$\text{Minimize}\ OF_3(X) = \sum_{t=1}^{12}\sum_{i=1}^{n}\sum_{j=1}^{l}(x_{ij}^{t} * PP_{ij}) \quad (3)$$

where PP_{ij} is the wastewater discharge amount per unit of supplied water (SW_{ij}) from sector j in the ith operational zone. PP_{ij} can be determined by PW_{ij}/SW_{ij}, where PW_{ij} is the amount of waste water and can be found in water resources bulletins.

2.3.2. System constraints

(i) Water balance equation

$$Q_i^t = Q_i^{t-1} + \sum_{k=1}^{m} RR_{k,i} * O_k^t + R_i^t + \sum_{j=1}^{l}(x_{i,j}^t * ret_{i,j}^t) - U_i^t - \sum_{j=1}^{l}(x_{i,j}^t) - TW_i^t, \quad (4)$$

where Q_i^t is the discharge of the ith operational zone at time t; Q_i^{t-1} is the discharge at $(t-1)$ time; m is the number of large-medium sized reservoirs; O_k^t is the release from the kth reservoir; $RR_{k,i}$ is the water connection ratio between the ith operational zone and the kth reservoir, and can be determined by the ratio of water diversion of the rivers between the kth reservoir and the ith operational zone, as provided by the Bureau of Hydrology of Changjiang Water Resources Commission in China; R_i is the sum of the water yield produced in the watersheds located up to the ith zone; x_{ij} and l are the variables as mentioned in Eq. (1); $ret_{i,j}^t$ is the return flow coefficient (dimensionless) which is greater than or equal to zero, and less than or equal to one; U_i^t is the amount of water loss including evaporation, seepage and loss during conveyances; TW_i^t is the amount of water transferred out of the basin.

(ii) Reservoir constraints

(a) The continuity equation for the kth reservoir can be written as follows:

$$S_k^t = S_k^{t-1} + I_k^t - O_k^t - EV_k^t \quad (5)$$

where S_k^t is the storage at time t; S_k^{t-1} is the storage at time t-1; I_k^t is the net reservoir inflow (excluding seepage) during the time t; O_k^t is the reservoir outflow during the time t; EV_k^t is the water loss due to evaporation during the time t.

(b) The storages for the kth reservoir are constraints based on physical limits:

$$S_{\min}^{kt} \leqslant S_k^t \leqslant S_{\max}^{kt} \quad (6)$$

where $S_{\min,k}^t$ is the minimum storage at time t and $S_{\max,k}^t$ is the maximum storage at time t.

(iii) Water demand constraints

$$x_{i,j}^t \leqslant DW_{i,j}^t \quad (7)$$

(iv) Water availability and non-negativity constraints

$$0 \leqslant \sum_{j=1}^{l} x_{i,j}^t \leqslant AWR_i^t \quad (8)$$

where AWR_i^t is the amount of the water available in the ith operational zone in the tth month.

Methods for determining the parameters shown in Eqs. (1)–(8) can be found in Liu et al. (2010, 2014).

2.3.3. Optimization techniques

As the water resources allocation model is complex (Yeh and Becker, 1982; Ming et al., 2015), it is difficult to arrive at an optimal solution. The genetic algorithm (GA), which is originally based on Darwin's evolution theory (Holland, 1975; Goldberg, 1989), is a heuristic (inexact), probabilistic (random), combinatorial (discrete), and search-based optimization technique. The continuing improvements of price/performance of computational systems have made the algorithm effective for various types of optimization (Holland, 1992) and widely used to solve problems concerning optimization with single or multiple objectives (Rauch and Harremoes, 1999; Van Dijk et al., 2002; Sarkar and Modak, 2003). The GA has also widely been used in the optimization of water resource systems (Janejira et al., 2005; Jothiprakash and Arunkumar, 2013). Therefore, the GA will be employed in our study to solve the optimal allocation model. Since the goal of this study is to assess the impacts of climate change on water systems and the effects of the corresponding adaptation measures, the three mentioned objective functions are further combined into a single objective optimization problem by the weighted sum method. As maximizing the function OF_2 is equivalent to minimizing the function $-OF_2$, the single objective optimization can be expressed as Eq. (9).

$$Miniminze\ F(X) = \sum_{i=1}^{3} (\omega_i \times O\tilde{F}_i(x_{i,j}^t)) \quad (9)$$

where $O\tilde{F}_i(X)$ is the normalized form of the ith objectives from its nondimensionalization and ω_i is the weight of the ith objectives which $\sum_{i=1}^{3}\omega_i$ equals to 1. We assume equal weight $(\omega_i = \frac{1}{3})$ in our study. The approach of normalizing the multi-objective functions OFs is to first optimize each of the objectives (OF_1, OF_2 and OF_3) individually and then divide each objective by those optimum values.

2.4. Responses of adaptation measures to the changing environment

To increase water availability during drought periods, Liu et al. (2010) and Liu et al. (2015) proposed a dynamic control of the flood limiting water level (FLWL) method for reservoir operation, which will be adopted in this study. The relevant alternatives concerning water saving ("demand-side" option) include the promotion of domestic water saving devices and irrigation styles, and reducing the leakage rate of water supply infrastructure, which will also be considered in the study. Therefore, the FLWL method for reservoir operation ("supply-side" option) and the water demand after the action of water saving ("demand-side" option) will be used as inputs for the optimal water resources allocation model and their effects on water resources allocation will be assessed in this study.

3. A case study in the mid-lower reaches of the Hanjiang River Basin

3.1. Study area

Hanjiang River is the largest tributary in the middle reaches of Yangtze River (Fig. 2) and serves as a water source for the Middle Route of South-to-North Water Transfer Project in China. The total area of the Hanjiang River Basin is 1,59,000 km^2. The areas of the upper and mid-lower reaches of the basin are 95,200 km^2 and 63,800 km^2 respectively. Danjiangkou Reservoir is located in Danjiangkou City, Hubei province and the water is fed directly to the middle route South-to-North Water Transfer Project. As Danjiangkou Reservoir is the boundary of the upper and mid-lower reaches of the Hanjiang River Basin, the water availability in the mid-lower reaches of the Hanjiang River Basin is impacted not only by climate change in the local area and the upper basin but also the transfer project and the reservoir's operation. About 15.3 million people lived in the mid-lower reaches of Hanjiang River in 2010, with 36.6% among them living in urban areas. Due to the fast growth of population and the rapid development of the local economy and urbanization, water demand is expanding and conflicts over water use are increasing substantially. As a very useful case study to help inform water resources management, the mid-lower reaches of Hanjiang River are evaluated in this paper to demonstrate the effectiveness of the adaptation measures on water resources allocation under varied water availability conditions.

To establish the optimal water resources allocation model, the water network in the study area is depicted in Fig. 3. According to the distribution of administrative counties (or cities) and rivers, 28 sub-basins are determined as the operational zones for the allocation model. Seventeen existing medium or large reservoirs, whose total capacity is more than 10 million m^3, are taken into account in the model (shown in Figs. 2 and 3).

3.2. Data

We use three groups of data in this study: hydrological data, water demand data series, and data on the characteristics of reservoirs for operation purposes. The first data set (hydrological data) is used to determine the available water resources. The area above Danjiangkou Reservoir accounts for 59% of the whole basin and its outflow serves as the inflow of the Danjiangkou Reservoir. Thus, the hydrologic processes of the upper area during climate change determine the South-to-North Water Transfer Project Scheduling and the reservoir operation, which can alter the available water resources in the mid-lower reaches. The rules applied for water

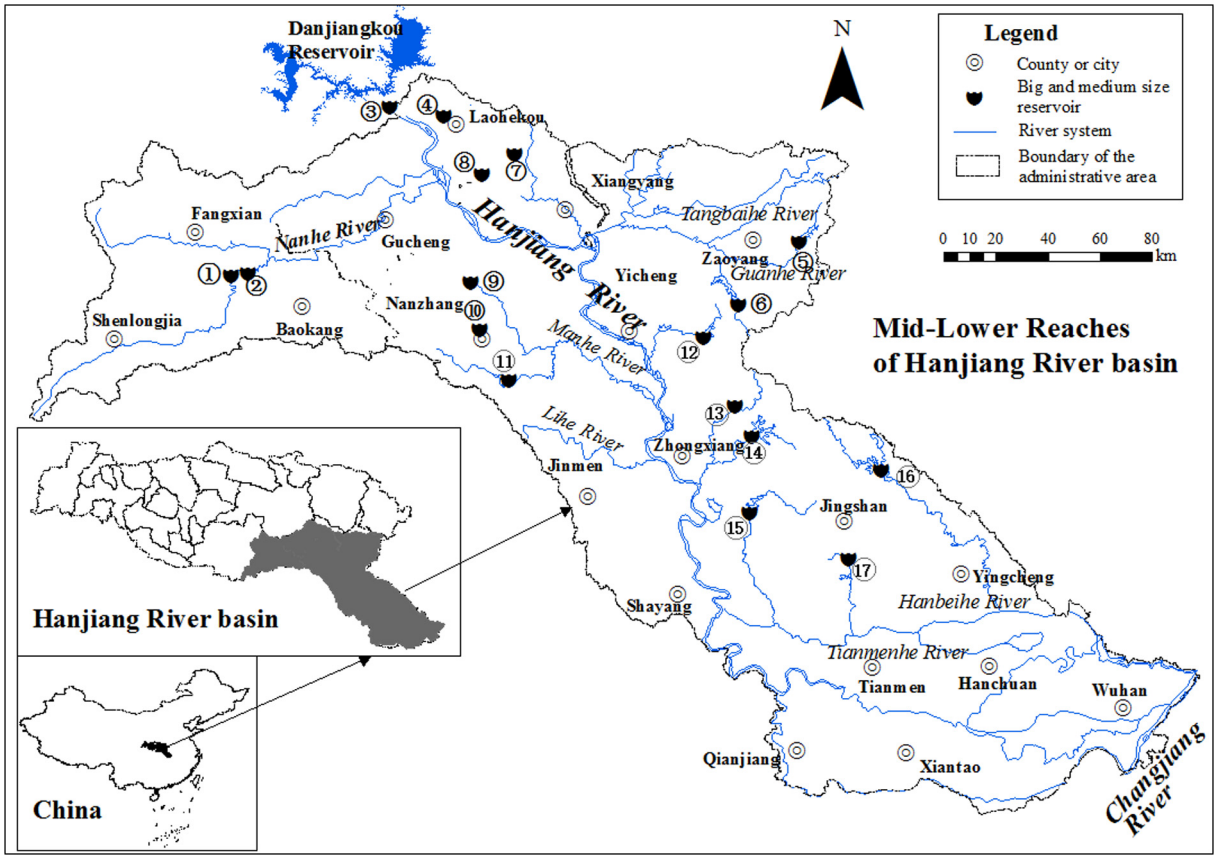

Fig. 2. Map of the study area.

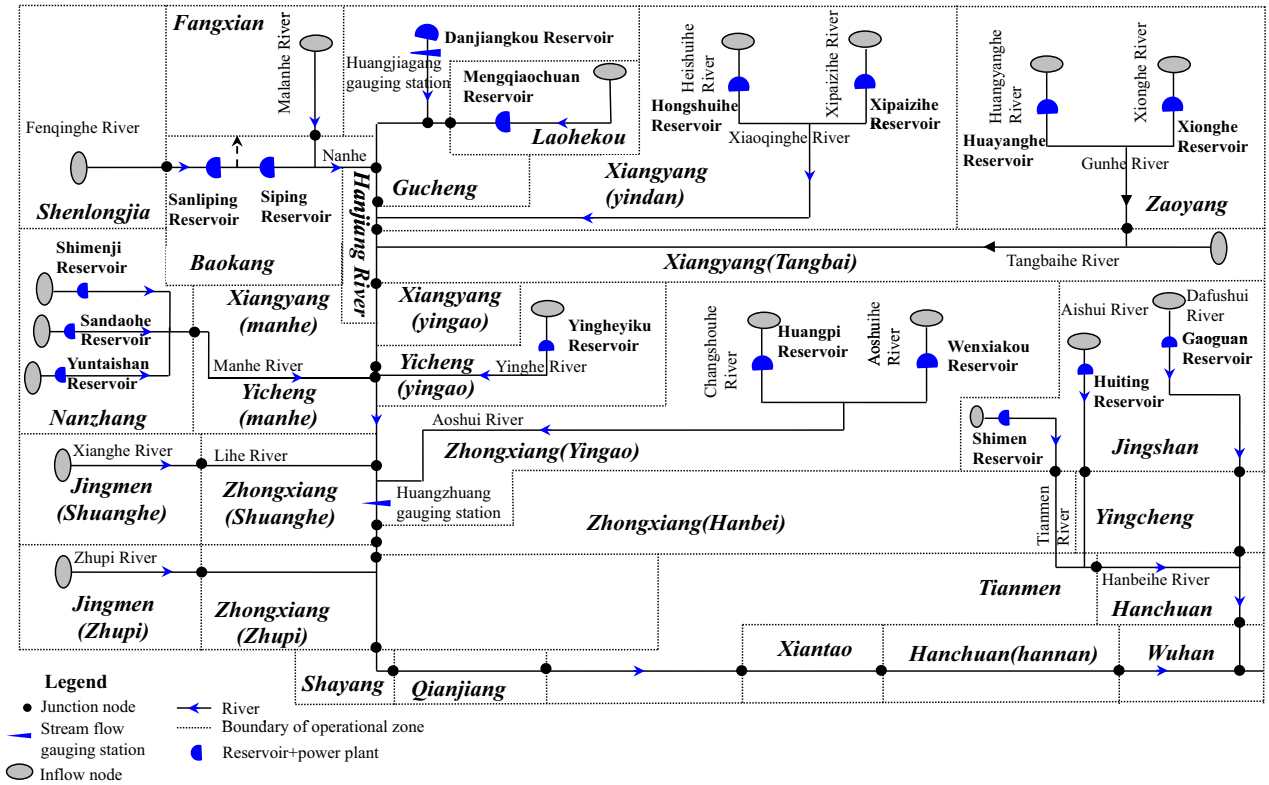

Fig. 3. Schematic diagram of the mid-lower reaches of the Hanjiang River Basin.

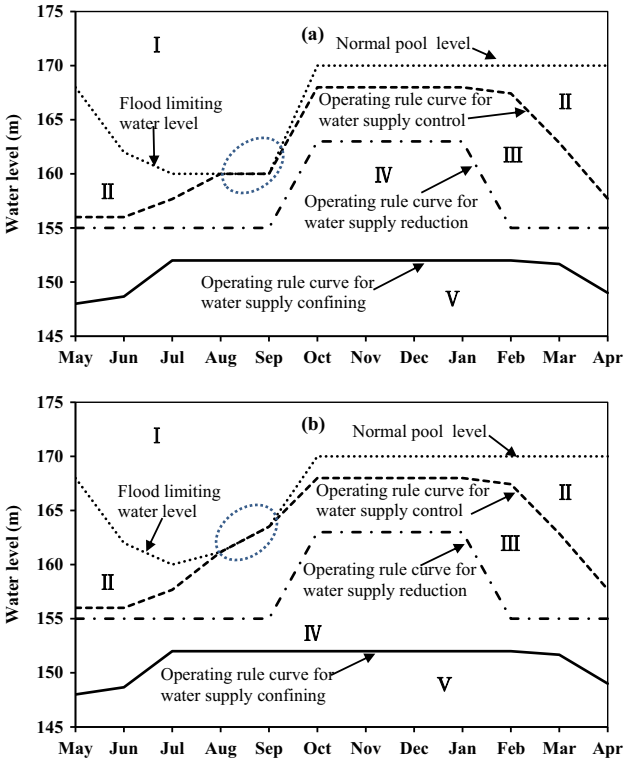

Fig. 4. Operating rule curves and zones for the Danjiangkou Reservoir: (a) Only one flood limiting level and (b) the dynamic control of FLWL. The area of bluish shaded circles shows the differences between (a) and (b).

supply operation in the South-to-North Water Transfer Project in Danjiangkou Reservoir are shown in Fig. 4 and are described as follows.

(1) If the reservoir water level is higher than the limit of flood water level (zone I), the discharge from water supply to the transfer project will not exceed 420 m^3/s, which is the maximum capacity of the project.
(2) If the reservoir water level is lower than the limit of flood water level but higher than the operating rule curve for water supply control (zone II), the discharge from water supply to the transfer project will not exceed 350 m^3/s.
(3) If the reservoir water level is lower than the operating rule curve for water supply control but higher than the operating rule curve for water supply reduction (zone III), the discharge from water supply to the transfer project will not exceed 300 m^3/s.
(4) If the reservoir water level is lower than the operating rule curve for water supply reduction but higher than the operating rule curve for water supply confining (zone IV), the discharge from water supply to the transfer project will not exceed 260 m^3/s.
(5) If the reservoir water level is lower than the operating rule curve for water supply confining (zone V), the discharge from water supply to the transfer project will not exceed 135 m^3/s.

There are 15 meteorological gauging stations with sufficient data series on daily precipitation and daily maximum and minimum air temperatures (1956–2010, shown in Fig. 5) in order to calibrate and validate the statistically downscaled results from the GCM. The meteorological data can be downloaded from the Climatic Data Centre, National Meteorological Information Centre, China Meteorological Administration. 261 precipitation gauging stations and 24 runoff gauging stations (provided by Bureau of Hydrology, Changjiang Water Resources Commission) with runoff data series from 1956 to 2010 are used to calibrate and validate the VIC hydrological model. For the projected future climate, the Beijing Climate Centre Climate System Model version 1.1 (BCC-CSM1.1) used in Coupled Model Intercomparison Project phase 5 (CMIP5) has been widely applied and provided a relatively good performance in reproducing observed climate variations of temperature and precipitation in China (Xin et al., 2013). We adopted two representative concentration pathway scenarios (RCP2.6 and RCP4.5) using simulations performed with the BCC-CSM1.1.

The second data set used in this study is comprised of water demand data series. In our present work, three water user sectors (agricultural, industrial, and domestic) were considered. To assess conservative water resources allocation plans (with a higher water supply guarantee rate), four types of agricultural water demand are adopted, with water inflow frequencies of 95%, 90%, 75%, and 50%. These inflows represent an extremely dry year, a very dry year, a dry year, and a normal year, respectively. The domestic water demand covers the rural area, cities, and towns. In the last two regions the domestic water demand should include the corresponding ecology demand which includes to ecological and environmental preservation and protection of urban green areas. While 2010 is the benchmark year, demands for 2020, 2030 and 2040 are also projected. Based on the expectation for social and economic development from the Bureau of Hydrology of Changjiang Water Resources Commission in China, GDP in the study area in 2020, 2030, and 2040 is projected to be 2.03, 3.89, and 7.12 times larger, respectively, than the benchmark value of GDP in 2010. However, the projected area for irrigation in 2020, 2030 and 2040 is 1.06, 1.07, and 1.07 times larger than the area in 2010, respectively, due to the "red line" farmland policy in China. According to the population structure and the China's child family policy, the population in study area in 2020, 2030 and 2040 is projected to be, respectively, 1.02, 1.09, and 1.13 times larger than in 2010. As water saving is one of the most effective adaptation measures to meet varying water availability conditions, this study does not only determine water demands under different economic and social development scenarios (shown in Table 1), but also estimates the water demands resulting from the implementation of water (shown in Table 2). All the water demand data (shown in Tables 1 and 2) are collected from the report on the comprehensive management plan on water resources for the Hanjiang River Basin, China (CWRC, 2011), which are estimated by the quota method. The in-stream ecology water demand is estimated by the Tennant method (Tennant, 1976).

The last data set used in this study contains the characteristics of reservoirs in the study area. There are 17 large to medium-sized reservoirs in the study area. The reservoir data are used as the model input, including total storage, reservoir storage at normal water level, dead storage, and reservoir storage at FLWL (shown in Table 3.). According to our proposed model, if there is enough water in the river for all water user sectors, the reservoir operations will be standard (i.e., maintaining the water level at the highest possible limit in order to maximize water storage). However, according to the Chinese Flood Control Act (The Standing Committee of the Eighth National People's Congress of the People's Republic of China, 1997), reservoir water levels are generally not allowed to exceed the FLWL, which is the highest limiting water level to provide adequate storage for flood prevention during flood season. In order to respond to the increasing water demand and the reduction of available water resources due to climate change, the dynamic control of the FLWL for reservoir operation, which is an effective adaptation measure and avoids exceeding the design risk, is proposed and implemented in China (Li et al., 2010, 2015). This dynamic control of FLML will be implemented in Sanliping and Danjiangkou Reservoirs, since only these two reservoirs can satisfy the requirements for the dynamic control (Li et al., 2010).

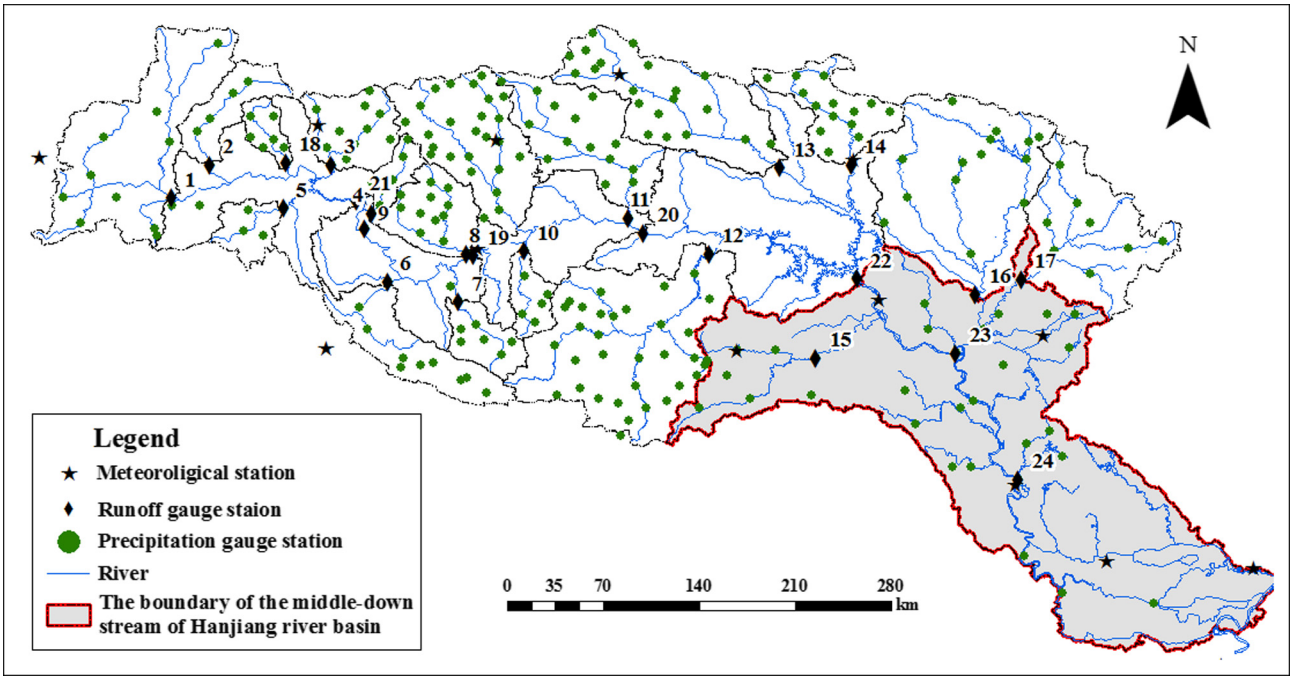

Fig. 5. Distribution of meteorological and hydrological gauge stations in the Hanjiang River Basin.

Table 1
Water demands under the economic and social development scenario (billion m^3).

Year	Agriculture*				Domesticity		Industry
	50%	75%	90%	95%	City and town	Rural area	
2010	5.57	6.36	7.11	7.67	0.34	0.22	4.52
2020	5.49	6.12	6.88	7.38	0.42	0.23	5.09
2030	5.16	5.73	6.41	6.89	0.52	0.24	5.36
2040	4.98	5.52	6.15	6.64	0.64	0.24	6.56

* The 95, 90, 75 and 50 percentile flows are statistical measure of local water resources and are based on annual rainfall records. These percentiles represent an extremely dry year (95%), a very dry year (90%), a dry year (75%) and a normal year (50%) respectively. *Source*: Data in Table 1 are sourced from the report on the comprehensive water resources management plan for the Hanjiang River Basin, China (CWRC, 2011)

Table 2
Water demands under the implementation of water saving measures (billion m^3).

Year	Agriculture				Domesticity		Industry
	50%	75%	90%	95%	City and town	Rural area	
2010	5.44	6.20	6.92	7.47	0.32	0.22	4.47
2020	5.25	5.85	6.56	7.02	0.40	0.23	4.72
2030	4.76	5.26	5.85	6.27	0.50	0.24	4.88
2040	4.54	5.01	5.52	5.93	0.62	0.24	5.93

Sources: Data in Table 2 are sourced from the report on the comprehensive water resources management plan for the Hanjiang River Basin, China (CWRC, 2011).

4. Results and discussion

4.1. Calibration and validation of the SDSM downscaling and hydrological model

The SDSM is applied to project daily surface temperature (particularly maximum (T_{max}) and minimum temperatures (T_{min})) and precipitation based on the National Centre for Environmental Prediction (NCEP, http://www.esrl.noaa.gov/psd/) reanalysis dataset and observations from 15 meteorological stations (including air temperature, solar radiation, humidity, wind speed, precipitation amounts and so on, available from http://data.cma.cn). The geographical domain, 102.5°E–115°E, 27.5°N–37.5°E, was chosen to include all areas with noticeable influence on the circulation patterns that govern weather in the Hanjiang Basin.

During the screening of downscaling predictors, the default values were found to have a confidence level of 95% and partial correlation (P.r.) of ±1. Selection of predictor variables was based on the explained variance and correlation between sets of predictors and single predictands (precipitation or temperature in this case) relationships analysed in SDSM 4.2. For precipitation, mean sea level pressure, 500 hPa geopotential height and specific humidity at 850 hPa were identified as the predictor set. Mean sea level pressure, mean surface air temperature at 2 m, 500 hPa geopotential height, 500 hPa zonal velocity, surface temperature at 850 hPa and mean surface air temperature at 2 m were considered as the predictors for temperature.

Table 3
Characteristics of the reservoirs in the mid-lower reaches of the Hanjiang River Basin.

No.	Reservoir name	Total storage	Reservoir storage at normal water level	Dead storage	Reservoir storage at flood limited water level*
1	Sanliping	510.00	211	261	389/468.54
2	Siping	269.00	247	102	127
3	Danjiangkou	33,910.00	29,050	12,690	22,910/25,790
4	Mengqiaochuan	110.33	88.15	2.7	90.85
5	Huayanghe	107.00	70.8	1.4	72.2
6	Xionghe	195.90	115.9	20	135.9
7	Xipaizihe	220.40	22	2.23	24.23
8	Hongshuihe	103.60	58.9	5.4	64.3
9	Shimenji	154.03	114.69	1.85	99
10	Sandaohe	154.60	127.42	0.02	127.44
11	Yuntaishan	123.00	89	5	89
12	Yinghe	121.66	76.31	3.62	79.93
13	Huangpi	125.61	70.25	10.1	63.62
14	Wenxiakou	520.00	269	176	388
15	Shimen	159.10	68.6	13	81.6
16	Gaoguan	201.08	154.32	30.89	145.91
17	Huiting	313.40	173.5	32.5	206

* There are two reservoirs at the flood limiting water level for the dynamic control of FLWL in Sanliping and Danjiangkou Reservoirs.

To calibrate and validate the prediction, we split the period (1961–2010) into two parts: the first part, from 1961 to 2000, is used for calibration and the remaining part, from 2001 to 2010, is used for validation. The performance of SDSM in downscaling monthly precipitation is shown in Fig. 6. The performance of daily T_{max} and T_{min} are assessed from the Nash–Sutcliffe efficiency (NSE) between the observed and SDSM-simulated series (shown in Tables 4 and 5).

The results in Tables 4 and 5 indicate an acceptable performance between the observed and simulated predictands. The predictands are monthly precipitation (P), daily T_{max} and daily T_{min} corresponding to the predictors in the calibration and validation periods. The NSE between the observed and simulated P, T_{max} and T_{min} during the calibration period (shown in Table 4) are reasonable since most of NSE values in the stations are above 0.70 for P, 0.90 for T_{max} and 0.94 for T_{min}. Since the precipitation from future scenarios and downscaling methods remains impossible to project with complete accuracy, the validity or accuracy of the model BCC-CSM1.1 combining the SDSM is often tested by its ability to accurately represent the historical climate. The results confirm the good applicability of SDSM and BCC-CSM1.1 in downscaling future precipitation and surface temperature for hydrologic simulation. The VIC distributed hydrological model (with the three soil layers model, VIC-3L model) in the Hanjiang basin was calibrated and validated by the daily runoff data obtained from 24 gauge stations (their data are available from Changjiang Water Resources Commission, China), daily maximum and minimum temperature data obtained from 15 gauge stations, and precipitation data collected from 261 gauge stations (their data are available from Changjiang Water Resources Commission, China) from 1980 to 1995 and 1996–2005, respectively. The NSE between the observed and simulated monthly runoff (R) during the validation period, with a range of 0.681 to 0.856 (shown in Table 5), suggests that the application of the VIC hydrological model for runoff simulation and prediction under the future climate change scenarios is successful.

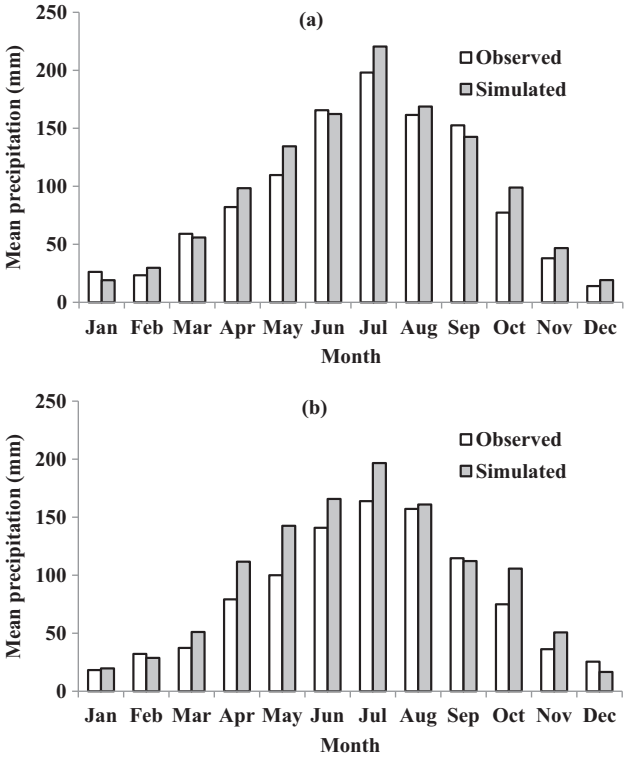

Fig. 6. Performance of the SDSM model on monthly mean precipitation during (a) calibration (1961–2000) and (b) validation (2001–2010) period.

4.2. Changes of water availability under climate change and water transfer project

The synthetic future daily data series of rainfall and temperature can be produced under RCP2.6 and RCP4.5 scenarios using the calibrated SDSM model in Section 4.1.

Under the stationary assumption that the determined temporal structure of climatology and the calibrated hydrological model parameters over the historical period are valid for use in the future, the available water resources can be determined through the calibrated VIC hydrological model in Section 4.1. To do this, two periods of time, a historical period (1961–2011), and a future period (2012–2099), are defined. The patterns of change of the future inflow of Danjiangkou Reservoir and the flow generation at the middle and lower reaches of the Hanjiang River Basin were then analysed. It is seen from Fig. 7 that under scenarios RCP2.6 and RCP4.5 at the middle and lower reaches of the Hanjiang River Basin, the streamflow during the dry season of a year in the future period (2012–2099) will decrease, while the streamflow during the flood seasons will increase during the years with frequencies of 50, 75, 90 and 95%. Opposite trends are found for the inflow results in Danjiangkou Reservoir (Fig. 8). The results are consistent with the

Table 4
NSEs of SDSM-downscaled daily T_{max}, daily T_{min} and monthly precipitation (P) between the observed and SDSM simulated series.

	Precipitation		T_{max}		T_{min}	
	Calibration period	Validation period	Calibration period	Validation period	Calibration period	Validation period
Lveyang	0.847	0.890	0.953	0.947	0.979	0.983
Foping	0.899	0.889	0.942	0.937	0.981	0.970
Shangxian	0.786	0.876	0.958	0.957	0.984	0.984
Zhenan	0.754	0.873	0.935	0.921	0.980	0.984
Xixia	0.638	0.854	0.956	0.948	0.986	0.986
Shiquan	0.747	0.885	0.957	0.947	0.985	0.987
Wanquan	0.760	0.886	0.962	0.961	0.982	0.985
Ankang	0.884	0.848	0.965	0.954	0.984	0.985
Fangxian	0.874	0.852	0.958	0.939	0.985	0.982
Laohekou	0.498	0.814	0.957	0.945	0.985	0.975
Zaoyang	0.281	0.877	0.962	0.956	0.983	0.973
Zhongxiang	0.622	0.781	0.964	0.955	0.984	0.977
Tianmen	0.437	0.760	0.966	0.950	0.981	0.965
Wuhan	0.467	0.732	0.965	0.952	0.977	0.943
Jiayu	0.690	0.723	0.966	0.949	0.981	0.968

Table 5
NSEs of runoff (R) between the observed and VIC simulated series.

Gauge station	Calibration period	Validation period	Gauge station	Calibration period	Validation period
Ankang	0.862	0.783	Wanfangdian	0.829	0.826
Baihe	0.887	0.792	Changqiangpu	0.798	0.791
Shiquan	0.900	0.840	Liukou	0.686	0.799
Huangjiagang	0.859	0.803	Xiangjiaping	0.798	0.834
Xiangyang	0.916	0.823	Guihuayuan	0.733	0.716
Huangzhuang	0.854	0.793	Changshaba	0.868	0.838
Hanzhong	0.783	0.740	Huanglongtan	0.701	0.687
Shenxiancun	0.696	0.682	Jingziguan	0.842	0.826
Youshuijie	0.748	0.751	Xixia	0.869	0.856
Lianghekou	0.703	0.848	Kaifengyu	0.800	0.713
Xixiang	0.595	0.581	Xindianpu	0.802	0.709
Machi	0.821	0.802	Guotan	0.812	0.713

finding that the mean precipitation will likely increase in many mid-latitude wet regions (IPCC, 2014), largely due to increasing of atmospheric moisture content. Since topography serves as a barrier to the monsoon winds coming from the east, precipitation will be intensified in the upstream mountain areas. The precipitation in plains areas (mid-lower reaches of the Hanjiang River Basin) will lessen.

Therefore, the available water resources from the upstream of the Hanjiang River Basin increase in the future, a potentially favourable outcome for water users. However, the South-to-North Water Transfer Project will transfer some of the water from the Danjiangkou Reservoir and reduce the total available water resources at the middle and lower reaches of the Hanjiang River Basin. The relevant alternatives concerning water saving and FLWL reservoir operation will alter the water demand and available water resources. Thus, the impacts of the water transfer project, water saving and FLWL, should be examined in order to optimize local water resources management, especially when the locally available water decreases.

In order to reduce the water shortage induced by climate change and the transfer project (human activities), the effects of adaptation water options (the dynamic control of the FLWLs for the reservoirs' operation and water saving measures in the study area) should be assessed.

4.3. Water resources allocation response to climate change and adaptation measures

As the water usage in an operational zone located in the upstream affects the downstream area, the released water from Danjiangkou Reservoir can be extracted by operational zones located along the main stream. As the rules of water supply operation for the South-to-North Water Transfer Project in Danjiangkou Reservoir (shown in Fig. 4) have been taken into account when assessing water demand in the study area, no water shortage is found in most of the operational zones along the main stream except Qianjiang. As there are two reservoirs (Danjiangkou and Siping Reservoirs) that satisfy dynamic control of FLWL, four types of operational zones are classified in the study area (shown in Fig. 9). If there is no water shortage in 2010, 2020, 2030 and 2040 in an operational zone, the zone is defined as the type A (shown in Fig. 9). If there is water shortage in one operational zone along the main stream in the study area, water supply might be influenced by the water transfer project through the operation of Danjiangkou Reservoir. This operational zone (Qianjiang) is defined as type B (shown in Fig. 9). Fangxian and Baokang are defined as type C (shown in Fig. 9), because water supply in these two operational zones is impacted by the FLWL operation. Type D in Fig. 9 is defined as the areas where water shortages can be found where water saving measures are in effect.

4.3.1. Impacts of variations of water resources availability on water resources allocation

The variations of water resources availability result from climate change and the South-to-North Water Transfer Project. The results of an impact assessment of climate change and of the South-to-North Water Transfer Project on the water resources allocation in the mid-lower reaches of the Hanjiang River Basin are shown in rose diagrams Figs. 10 and 11. The colour of arc line (radii boundaries) and fan shape (area) in these two figures represents the frequency level (that is the probability of non-occurrence of the drought event) referring to the available water resources, while

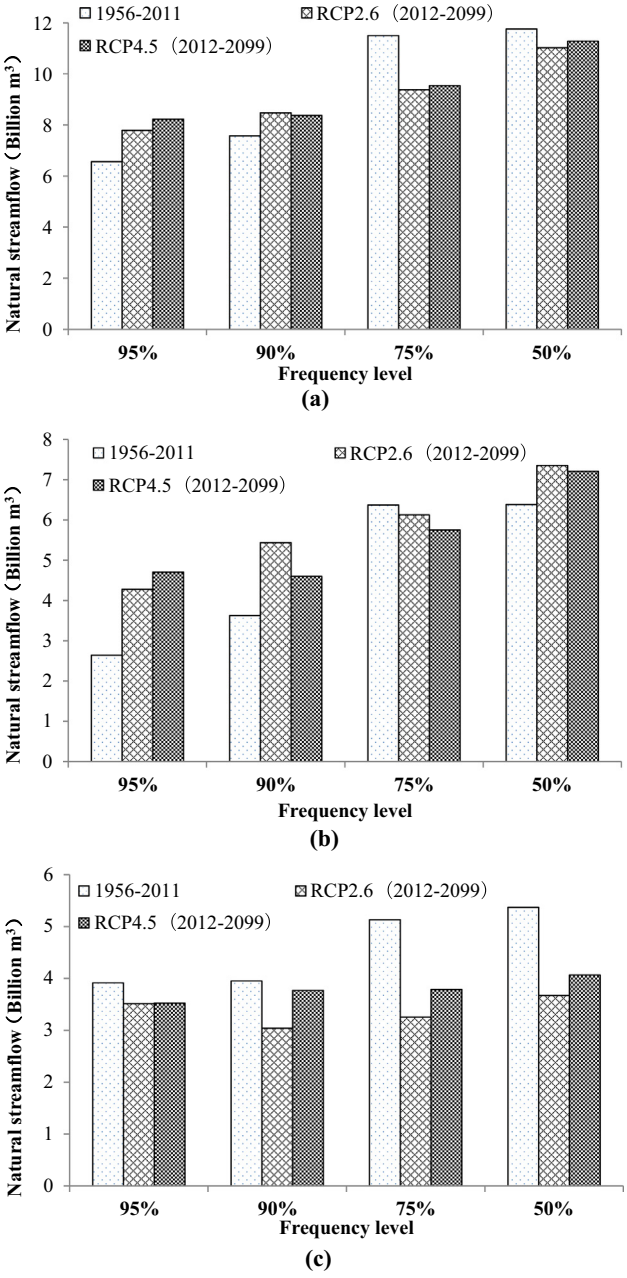

Fig. 7. Results of historical (1956–2011) and predicted (2012–2099) streamflows in mid-lower reaches of the Hanjiang River Basin from BCC-CSM1.1 under RCP 2.6 and RCP 4.5. (a) a year; (b) flood season (April to September); (c) dry season (October to March).

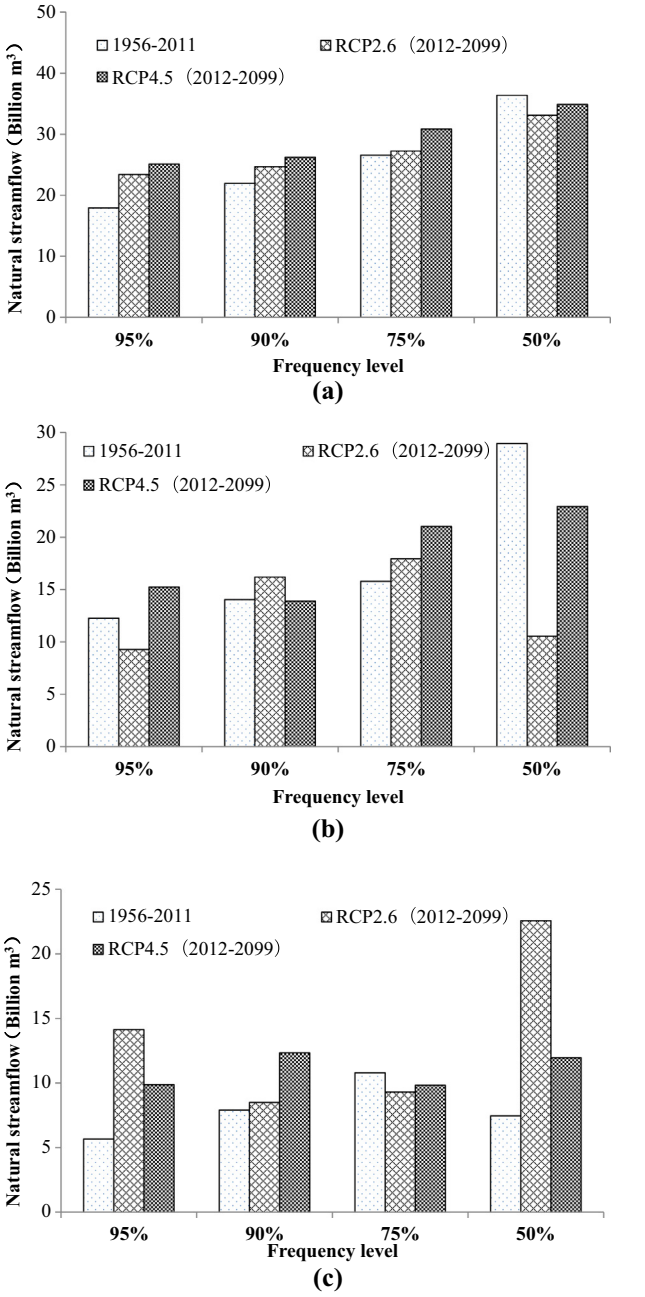

Fig. 8. Results of historical (1956–2011) and predicted (2012–2099) streamflow in Danjiankou Reservoir from BCC-CSM1.1 under RCP 2.6 and RCP 4.5. (a) one year; (b) flood season (April to September); (c) dry season (October to March).

the arc line is the water demand at the frequency level and the arc polygon is the responding allocated water result. The gap between the arc line (water demand) and the fan shape (allocated water resources) represents the amount of water shortage. Four planning level years (2010, 2020, 2030, and 2040) are shown in the four quadrants of the Cartesian coordinate system. Three scenarios (the historical period 1956–2011 and predicted water flows from RCP 2.6 and RCP 4.5) are employed in each planning level year. Four frequencies (95%, 90%, 75%, and 50%) of water inflow are adopted in each scenario. Therefore, 48 ($4 \times 3 \times 4$) types of allocation results in an operational zone are shown in one chart in a concise way to present the impact of various factors on resource allocation.

As the water demand under the economic and social development scenario is increasing in Shenglongjia, Gucheng, Nanzhang, Xiangyang (Tangbai), Zaoyang, and Jingmen (Zhupi) operational zones shown in Table 1 (denoted as type D in Fig. 9) at frequency levels of 95%, 90%, 75%, and 50% in 2010, 2020, 2030 and 2040 respectively, the allocated water in these operational zones will generally increase. However, the allocated water depends on not only water demand but also on available water resources. As a result, the colours representing the allocated water in each frequency level are in a different order in the different years. The minimum allocated water among the four frequency levels in type D operational zones is 50% (shown as fan shape in purple) except the Jingmen (Zhupi) which is 90% (shown as fan shape in blue). The maximum water demand among the four frequency levels is the 90% while the maximum water resources are at the 50% frequency level. As the allocated water under the 50% frequency level

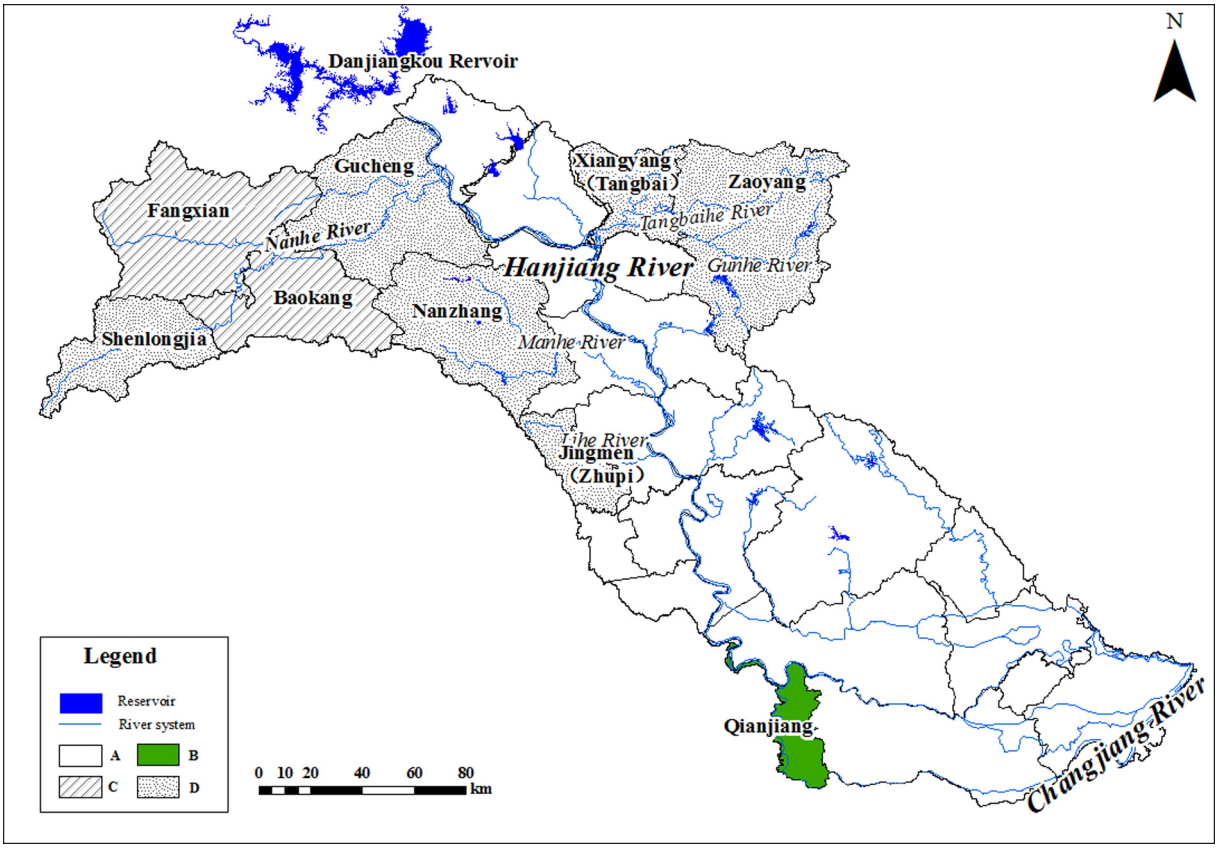

Fig. 9. A, B, C, and D types of water shortage in mid-lower reaches of the Hanjiang River Basin according to the optimal water resources allocation results. A: there is no water shortage; B: water shortage happens along the main stream and water supply might be influenced by the water transfer project; C: water supply is impacted by the FLWL operation; D: water shortage can be reduced by the water saving measures.

is more than the one under the 95% frequency level in Jingmen (Zhupi) operational zone, the amount of allocated water in Jingmen (Zhupi) operational zone mainly depends on available water resources rather than water demand. The monthly available water resources are quite unevenly distributed at the 90% and 95% frequency levels (shown in Fig. 7), and most of the water demand is from agriculture (shown in Tables 1 and 2). The agricultural sector is heavily influenced by climate factors while the industrial and domestic sectors are comparatively stable during climate change (Bell et al., 2014). Thus, since most demand comes from the agricultural sector, water resource allocations are heavily influenced by climate change. As shown in Fig. 3, there are no reservoirs in Jingmen (Zhupi) and Shenglongjia operational zones, and their historical (1956–2011) allocation water results are greater in number than those in the future predicted water flow under RCP 2.6 and RCP 4.5. In the other four operational zones, the allocated water resources calculated under the historical scenarios are the same as those calculated for the future scenarios. The main reason for this is that the reservoirs satisfy the water demand by adjusting water flow under future scenarios. As the total available water resources are predicted to decrease in the future, especially during the dry season according to RCP 2.6 or RCP 4.5 scenarios (shown in Section 4.2), and since there are not enough reservoirs to adjust the available water to the demand, water shortages in the operational zones situated around the boundary of the basins such as Jingmen (Zhupi) and Shenglongjia, will become increasingly serious in the future.

Qianjiang (type B, shown in Fig. 9) is located downstream of the Danjiangkou reservoir which provides water for the South-to-North Water Transfer Project. As the instream ecological water demand is sensitive to Danjiangkou Reservoir operations in this area, water shortage occurs under the historical scenario (shown in Fig. 11(b)) and the South-to-North Water Transfer Project proceeds according to its operational rules (shown in Section 3.2). If the effects of the transfer project are removed, there is no water shortage in Qianjiang (shown in Fig. 11(a)). Water inflow in Danjiangkou Reservoir will increase in the future under RCP2.6 and RCP4.5, but the increased inflow cannot completely satisfy the South-to-North Water Transfer Project at the monthly scale. Additionally, the decreasing amount of water shortage in Qianjiang is not equal or linearly related to the increasing amount of inflow into the Danjiangkou Reservoir, due to the uneven spatial and temporal distribution of increasing inflow and the nonlinear operation rule in Danjiangkou Reservoir.

4.3.2. Effects of dynamic control of the FLWL for the reservoirs' operation on water resources allocation

Fig. 12 illustrates the effect of the dynamic control of FLWL for the reservoirs' operation on water resources allocation in Qianjiang (influenced by Danjiangkou Reservoir), Fangxian and Baokang (influenced by Sanliping Reservoir). For all optimal water resources allocation results in these three operational zones, more water was allocated after the application of the dynamic control of FLWL. Specifically, (1) the amount of water allocated in Qianjiang is more than that in Fangxian and Baokang, because Th Danjiangkou Reservoir is larger than Sanliping Reservoir; (2) compared with the Fig. 12. (a) (including Qianjiang, Fangxian and Baokang), the effects of the dynamic control of FLWL on increasing allocated water is more significant at the 95% frequency level, especially under the

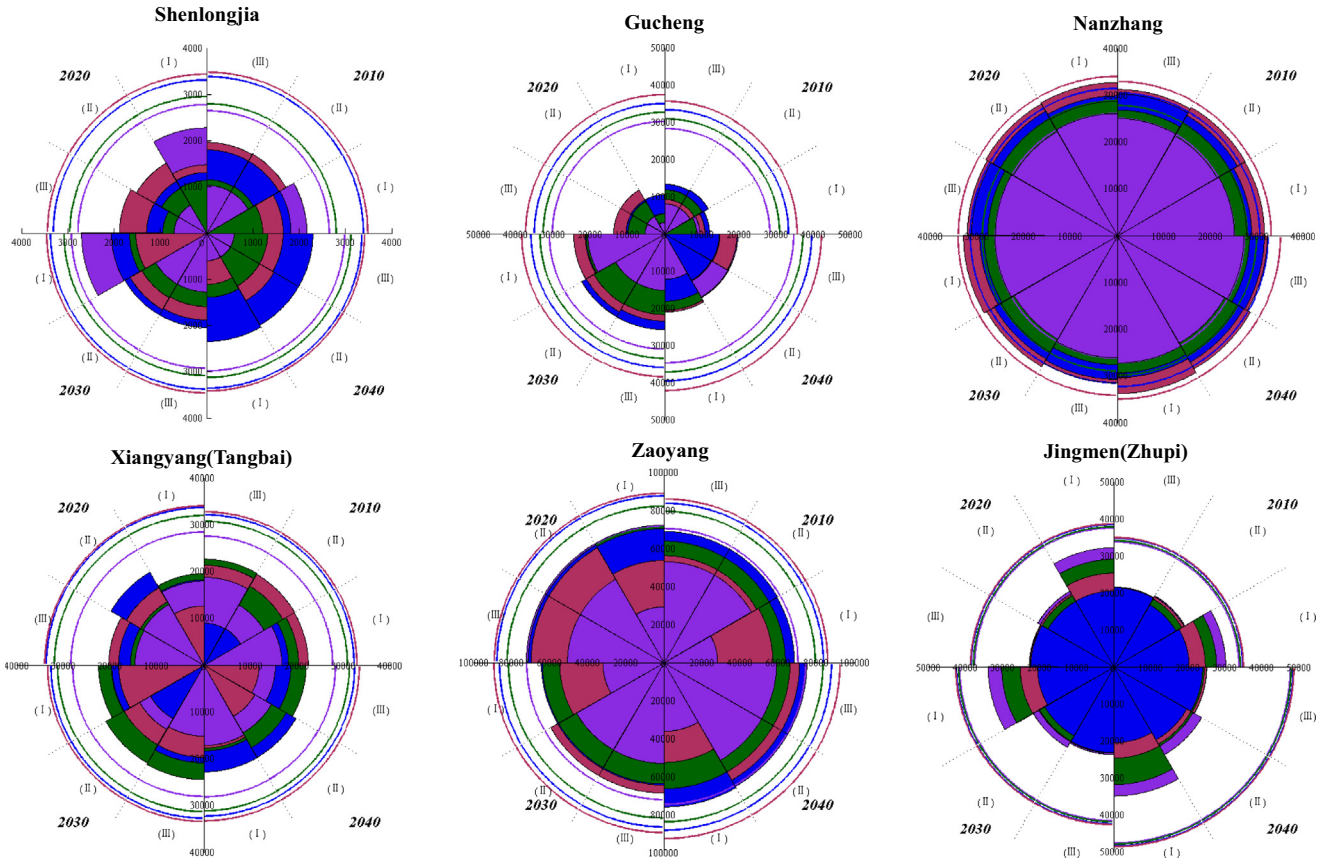

Fig. 10. Water allocation results in the type D operational zone under the planned economic and social development conditions. "", "", "", and "" (arc lines, radii boundaries) show the amount of water demand at 95%, 90%, 75%, and 50% frequency level. "", "", "", and "" (fan shape, area) show the allocated water at 95%, 90%, 75%, and 50% frequency level. (I), (II) and (III) show the conditions for the water demands and are the historical (1956–2011) and predicted water flow from RCP 2.6 and RCP 4.5 respectively.

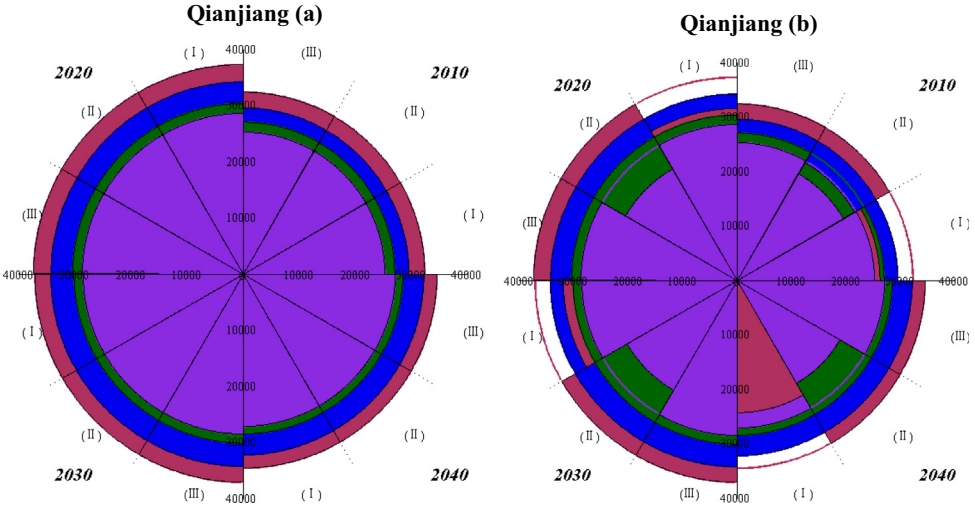

Fig. 11. Water allocation results in type B operational zone under the planned economic and social development conditions. (a): without South-to-North Water Transfer Project running; (b): considering South-to-North Water Transfer Project. "", "", "", and "" (arc lines, radii boundaries) show the amount of water demand at 95%, 90%, 75%, and 50% frequency level. "", "", "", and "" (fan shape, area) show the allocated water at 95%, 90%, 75%, and 50% frequency level. (I), (II) and (III) show the historical (1956–2011) and predicted water flow from RCP 2.6 and RCP 4.5 respectively.

historical scenario, since more flood water was stored in the reservoir and then released during the dry season.

It is worth noting that water shortage will become more severe under the future scenarios (RCP2.6 and RCP 4.5) than under historical scenarios in Fangxian and Baokang operational zones. Although more water can be gained from the implementation of the dynamic control of FLWL adaptation measures in Sanliping Reservoir for Fangxian and Baokang operational zones, the locally available water cannot satisfy water demand in every scenario and in every year, especially in the Baokang operational zone.

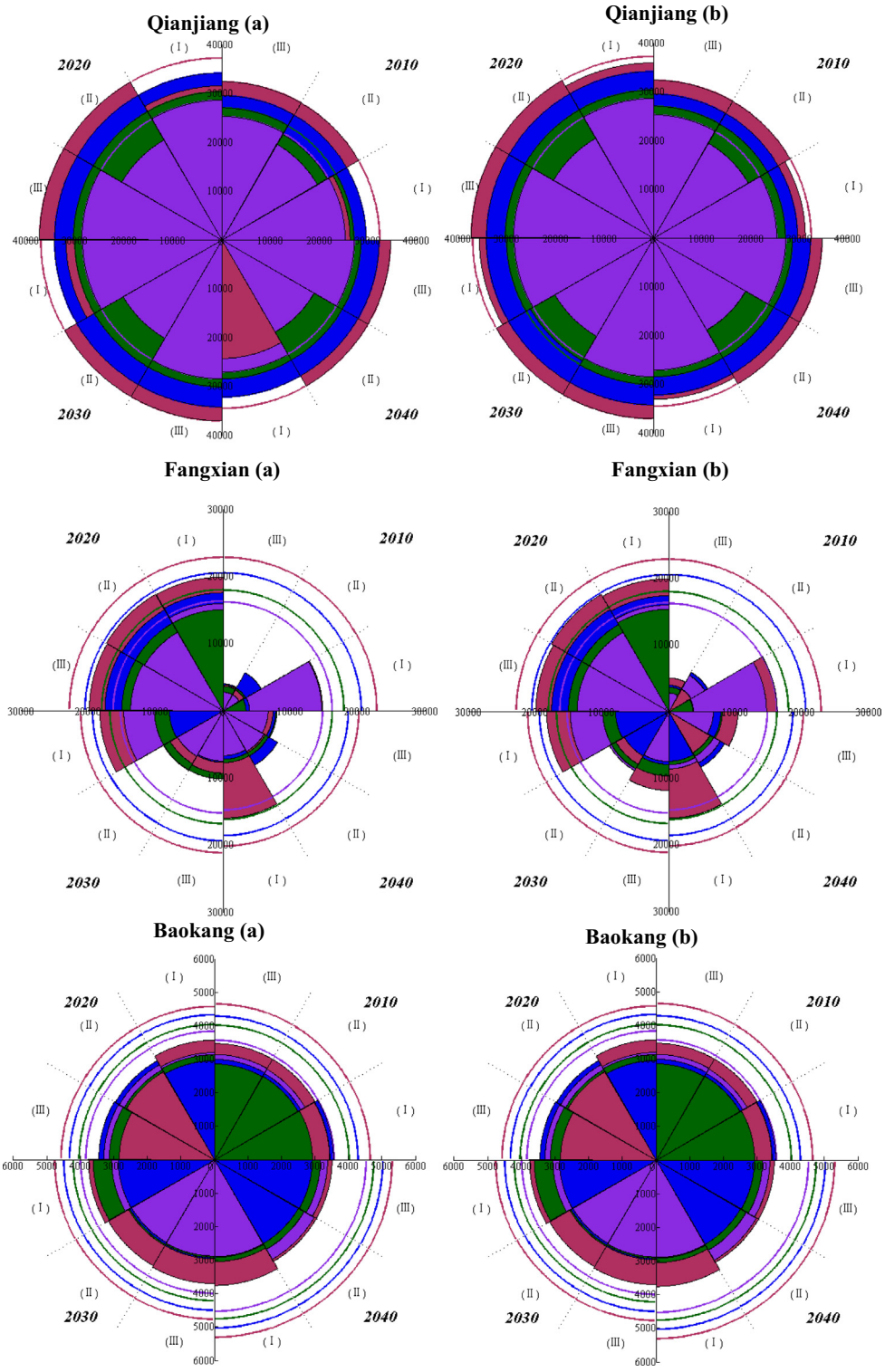

Fig. 12. Water allocation results in type B and C operational zone under the planned economic and social development conditions. (a): without the dynamic control of the FLWL; (b) considering the dynamic control of the FLWL. "", "", "", and "" (arc lines, radii boundaries) show the amount of water demand at 95%, 90%, 75%, and 50% frequency level. "", "", "", and "" (fan shape, area) show the allocated water at 95%, 90%, 75%, and 50% frequency level. (I), (II), and (III) show the historical (1956–2011) and predicted water flow from RCP 2.6 and RCP 4.5 respectively.

4.3.3. Role of water saving alternatives in water resources allocation

Water saving is an effective option for water resources management. As the relationship between water demand and available water resources is nonlinear, and optimal water resources allocation is an integral part of a basin system, water saving alternatives not only influences optimal water resources allocation in an operational zone, but also alleviate the extent of water shortage in the whole basin. The possible effects of planned water saving alternatives on water demand in the future can be found in the report on the comprehensive management plan on

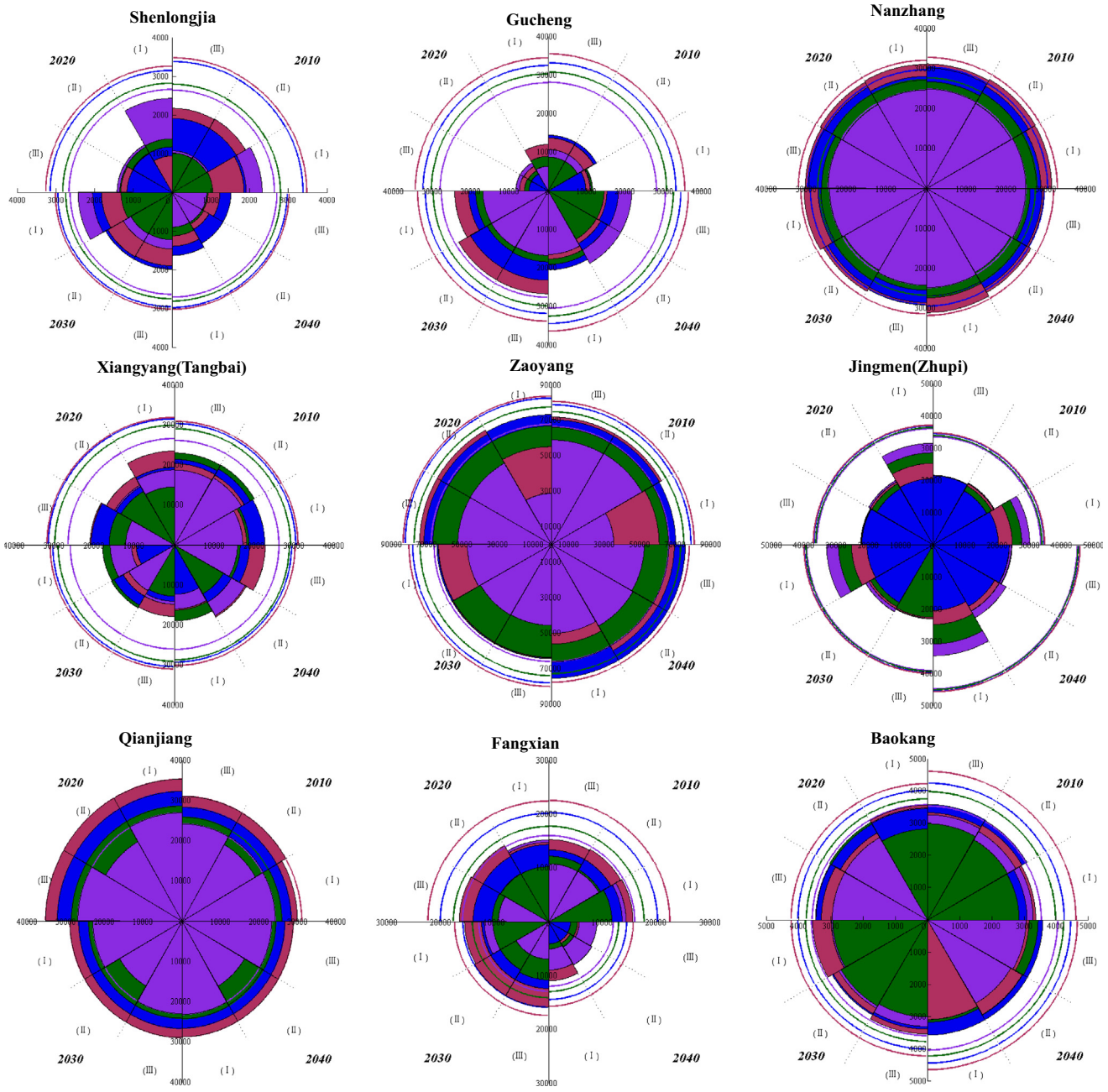

Fig. 13. Water allocation results in type B, C and D operational zone under the implementation of water saving measure conditions. "", "", "", and "" (arc lines, radii boundaries) show the amount of water demand at 95%, 90%, 75%, and 50% frequency level. "", "", "", and "" (fan shape, area) show the allocated water at 95%, 90%, 75% and 50% frequency level. (I), (II) and (III) show the historical (1956–2011) and predicted water flow from RCP 2.6 and RCP 4.5 respectively.

water resources for the Hanjiang River Basin, China (CWRC, 2011), in the form of water demands following the implementation of water saving measure (shown in Table 2).

As shown in Fig. 13, the extent of water shortage in most scenarios was reduced (radii boundaries in Fig. 13 are reduced) compared to the results shown in Fig. 10, Figs. 11(b) and 12(b) under the same allocation conditions but using different water demand alternatives (shown in Tables 1 and 2). The allocated water in Nanzhang, Zaoyang and Qianjiang operational zones can satisfy most of their water demands following the implementation of water saving measure. However, water shortages remain a serious problem in Shenglongjia, Gucheng, Xiangyang (Tangbai), and Jingmen (Zhupi), where the maximum allocated water is less than the water demand at the 50% frequency level under the implementation of water saving measure. Water shortage under the future scenarios (RCP2.6 and RCP4.5) is more serious than under the historical scenarios in Shengloangjia and Jingmen (Zhupi), while the opposite trend is observed in Gucheng. As these four operational zones are located at the source of the tributaries in Hanjiang, it is not feasible to transfer or allocate the water from the Danjiangkou Reservoir to these areas. Therefore, unconventional water resources such as storm water might be good options to satisfy the water demand. Water shortages in Fangxian and Baokang are less severe and occur mainly in the regional agricultural sector. Strategies for allocating water to meet the instream ecology requirements and human demand will be improved in the future.

5. Conclusion

The results of our case study show that the uneven distribution and changes of available water resources will increase the risk of water shortage, especially in the optimal water resources allocation operational zones located on the boundaries of the basin, where not only is available water reduced, but available adaptation measure are fewer, and the effects of the measures not as significant as in locations downstream of the tributary or reservoirs. The analysis of the adaptation measures demonstrates that water saving and the dynamic control of reservoir operations by FLWL can alleviate water shortages, and that their effects on optimal water resources allocation is nonlinear. The negative impacts of water transfer projects can be avoided through the dynamic control of reservoirs by FLWL under all the historical and future RCP2.6 and RCP4.5 scenarios. However, it should be kept in mind that these two conventional adaptation measures are not a complete solution. Unconventional adaptation measures (such as the harvest and use of storm water) should also be implemented to solve water shortage problems in this area.

In summary, climate change will bring different challenges and opportunities to different places. Adaptation measures including water saving, flexible reservoir operation and storm water gathering can be adopted to solve the problems of water shortage induced by climate change or water transfer projects on the variability of water resources availability. This research has proposed a framework for assessing the effects of adaptation measures on water resources allocation through an optimal water resources allocation model. The optimal model combined climate change and human activities (land use/cover and water transfer projects) to consider the variability of water resources availability, therefore, the framework proposed in this paper shows quantitatively the effects of adaptation measures to changing environments and will contribute to the support of water management and adaptation choice or policy-making, reflecting the multi-dimensional aspects of optimal water resources allocation.

As the framework for assessing the effects of adaptation measures on water resources allocation under varied water availability conditions includes GCM, downscaling methods, hydrological models, water demand estimation and optimal allocation models, there are some uncertainties presented in the assessment. Available datasets are rarely sufficient for calibrating and validating all the required parameters. Furthermore, interacting uncertainties can often become very complex. It is important to assess the uncertainty of the assessments in order to determine the level of risk, which will be a topic of future research. However, the results found in this study still offer useful guidelines for local and international water resources management.

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